Digital Elevation Models of the U.S. Virgin Islands:
Procedures, Data Sources and Analysis

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1. INTRODUCTION

In July of 2014, the National Geophysical Data Center (NGDC), an office of the National Oceanic and Atmospheric Administration (NOAA), developed bathymetric–topographic digital elevation models (DEMs) of the U.S. Virgin Islands (Figure 1). Two 1/3 arc-second[1] DEMs depicting Sts. John–Thomas and St. Croix referenced to mean high water (MHW) and one 1 arc-second regional DEM depicting the the U.S. Virgin Islands were carefully developed and evaluated. The DEMs will be used as input for the Method of Splitting Tsunami (MOST) model developed by the Pacific Marine Environmental Laboratory (PMEL) NOAA Center for Tsunami Research (http://nctr.pmel.noaa.gov/) to simulate tsunami generation, propagation and inundation. The DEMs were generated from diverse digital datasets in the region (grid boundaries shown in Figure 2). The DEMs will be used for tsunami inundation modeling, as part of the tsunami forecast system Short-term Inundation Forecasting for Tsunamis (SIFT) currently being developed by PMEL for the NOAA Tsunami Warning Centers. This report provides a summary of the data sources and methodology used in developing the U.S. Virgin Islands DEMs.
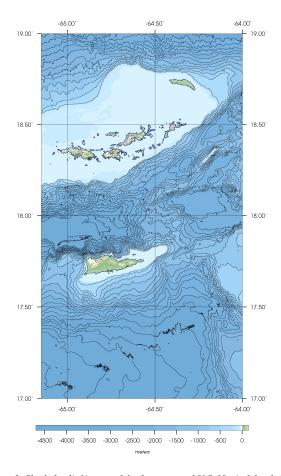
Figure 1. *Shaded-relief image of the 1 arc-second U.S. Virgin Islands DEM*

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[1]The U.S. Virgin Islands DEMs are built upon a grid of cells that are square in geographic coordinates (latitude and longitude), however, the cells are not square when converted to projected coordinate systems, such as UTM zones (in meters). At the latitude of the U.S. Virgin Islands, 1/3 arc-second of latitude is equivalent to 10.29556 meters; 1/3 arc-second of longitude equals 7.95 meters

2. STUDY AREA

The coastal U.S. Virgin Islands DEMs cover the three major islands of the Virgin Islands: St. John, St. Thomas and St. Croix. (Figure 2).

Table 1. Specifications for the U.S. Virgin Islands DEMs

Grid Area	U.S. Virgin Islands
Coverage Area	-65.15 °, 17.0 °, -64.0 °, 19.0 °
Coordinate System	Geographic decimal degrees
Horizontal Datum	World Geodetic System 1984 (WGS 84)
Vertical Datum	Mean High Water (MHW)
Vertical Units	Meters
Grid Spacing	1/3 arc-second
Grid Format	Arc ASCII Grid

Figure 2. *Extents of the U.S. Virgin Islands project area*
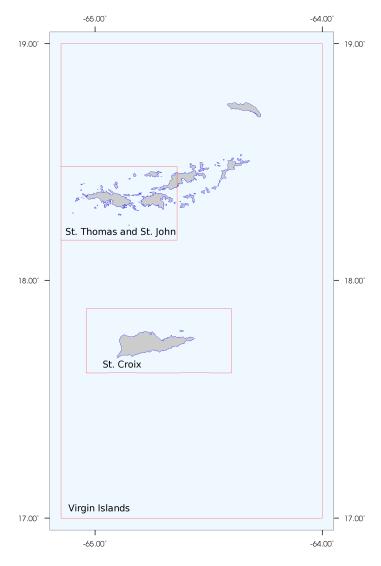
3. SOURCE ELEVATION DATA

The best available high resolution digital data were obtained by NGDC and shifted to common horizontal and vertical datums: North America Datum 1983 (NAD 83)[2] and VIVD09 (Virgin Islands Vertical Datum of 2009). Data were gathered, where available, in an area slightly larger (∼5%) than the DEM extents. This 'data buffer' ensures that gridding occurs across rather than along the DEM boundaries to prevent edge effects. Data processing and evaluation, and the DEM assembly and assessment are described in the following subsections.

3.1 Data Sources And Processing

Coastline, bathymetric, and topographic digital datasets (Table 2) were obtained from NOAA's NGDC, NGS and Coastal Services Center (CSC); the United States Geological Survey (USGS); the United States Army Corps of Engineers (USACE). The datasets were displayed with Earth Systems Research Institute (ESRI) ArcGIS, ESRI Imagery World 2D Online World Imagery, and Applied Imagery Quick Terrain Modeler software (QT Modeler) to assess data quality and manually edit datasets. Vertical datum transformations between VIVD09, MHW and MLLW were accomplished using NOAAs Vertical Datum Transformation (*VDatum*)[3] software. (see Section 3.2.1).

Table 2. Topographic and Bathymetric Datasets Used in Compiling the U.S. Virgin Islands DEMs

Source	Year	Data Type	Spatial Resolution	Original Horizontal Datum/Coordinate System	Original Vertical Coordinate System	URL
NGDC St. Croix	2008	DEM	10 meters	WGS 84 geographic	MHW (meters)	http://ngdc.noaa.gov
NGDC St. Thomas and St. John	2008	DEM	10 meters	WGS 84 geographic	MHW (meters)	http://ngdc.noaa.gov
NGDC U.S. Virgin Islands	2008	DEM	30 meters	WGS 84 geographic	MHW (meters)	http://ngdc.noaa.gov
USGS USVI Topobathy	2003	bare-earth lidar	1 - 5 meters	WGS 84 geographic	VIVD09 (meters)	http://digitalcoast.noaa.gov
USACE USVI Topobathy	2007	bare-earth lidar	1 - 5 meters	WGS 84 geographic	VIVD09 (meters)	http://digitalcoast.noaa.gov
NOAA USVI Topobathy	2011	bare-earth lidar	1 - 5 meters	WGS 84 geographic	VIVD09 (meters)	http://digitalcoast.noaa.gov
NOAA/NOS	2006-2010	NOS hydrographic soundings (BAG)	1:10000 meters	UTM Zone 20	Mean Lower Low Water (MLLW)	http://ngdc.noaa.gov

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[2]The horizontal difference between NAD 83 and World Geodetic System of 1984 (WGS 84) geographic horizontal datums is approximately one meter across the contiguous U.S., which is significantly less than the cell size of the DEM. Many GIS applications treat the two datums as identical, so do not actually transform data between them, and the error introduced by not converting between the datums is insignificant for our purposes. NAD 83 is restricted to North America, while WGS 84 is a global datum. As tsunamis may originate most anywhere around the world, tsunami modelers require a global datum, such as WGS 84 geographic, for their DEMs so that they can model the waves passage across ocean basins. This DEM is identified as having a WGS 84 geographic horizontal datum even though the underlying elevation data were typically transformed to NAD 83 geographic. At the scale of the DEM, WGS 84 and NAD 83 geographic are identical and may be used interchangeably.

[3]*VDatum* is a free software tool being developed jointly by NOAA's NGS, OCS, and CO-OPS. *VDatum* is designed to vertically transform geospatial data among a variety of tidal, orthometric and ellipsoidal vertical datums.

3.2   Establishing Common Datums

3.2.1   *Vertical datum transformations*

Datasets used in the compilation and evaluation of the U.S. Virgin Islands DEMs were originally referenced to several vertical datums including VIVD09, MHW and MLLW. All datasets were transformed to VIVD09 using *VDatum.*

3.2.2   *Developing the conversion grid*

Using extents slightly larger (∼5%) than the U.S. Virgin Islands project area, an initial *xyz* file was created that contained the coordinates of the four bounding vertices and midpoint of the larger extents. The elevation value at each of the points was set to zero. The GMT command 'surface' was used to apply a tension spline to interpolate cell values making a zero-value 3 arc-second grid. This "zero-grid" was then converted to an intermediate *xyz* file using the GMT command 'grd2xyz'. Conversion values from MHW to VIVD09 and MLLW to VIVD09 at each *xyz* point were generated using *VDatum* and the null values were removed.

The median-averaged *xyz* file was then interpolated with the GMT command 'surface' to create a 1/3 arc-second and 1 arc-second 'VIVD09 to MHW' and 'MLLW to VIVD09' conversion grids with the extents of the buffered U.S. Virgin Islands project area, representing the differences between the datums onshore to the DEM extents.

3.2.3   *Assessing accuracy of conversion grid*

The conversion grids were assessed using NOS survey data. For testing of this methodology, the NOS hydrographic survey data were transformed from MLLW to VIVD09 using *VDatum*. The resultant *xyz* files were filtered to remove any null values and then were merged together to form a single *xyz* file of the NOS hydrographic survey data with a vertical datum of VIVD09. A second *xyz* file of NOS data was created with a vertical datum of MHW using the same method. Elevation differences between the MHW and VIVD09 *xyz* files were computed. The same method was used to assess the 'MHW to VIVD09' conversion grid.

To verify the conversion grid methodology, the difference *xyz* file was used to generate a histogram using Gnuplot[4] to evaluate the performance of the 1/3 arc-second conversion grids by comparing 'MHW to VIVD09' and 'MLLW to VIVD09' conversion grids to the combined difference *xyz* files from the *VDatum* project area.

3.2.4   *Horizontal datum transformations*

Datasets used to build the U.S. Virgin Islands DEMs were downloaded or received referenced to WGS 84 geographic or NAD 83 geographic horizontal datums. The relationships and transformational equations between these horizontal datums are well established. Data were converted to a horizontal datum of NAD 83 geographic using *Proj4* and *VDatum*.[5]

3.2.5   *Verifying consistency between datasets*

After horizontal and vertical transformations were applied, the ascii *xyz* files were reviewed for consistency between datasets. Problems and errors were identified and resolved before proceeding with subsequent gridding steps.

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[4]Gnuplot is an open-source command-driven interactive function plotting program. It can be used to plot functions and data points in both two- and three-dimensional plots in many different formats. It is designed primarily for the visual display of scientific data.

[5]Proj4 (a free standard Unix filter function which converts geographic longitude and latitude coordinates into cartesian coordinates, $(\lambda, \phi) \rightarrow$ (x, y), by means of a wide variety of cartographic projection functions) was used to horizontally transform datasets that originated in a State Plane datum before vertical transformations were performed using *VDatum*, which did not support state plane transformations at the time of development.

4. DEM DEVELOPMENT

4.1 Building the VIVD09 DEM

Detailed boundaries of all recent lidar and bag data were generated in order to clip NGDCs previously developed MHW DEMs of the U.S. Virgin Islands. The clipped DEMs were then converted to *xyz* data and transformed to VIVD09 using the appropriate conversion grid. The resultant VIVD09 *xyz* data were used as source data covering the areas which did not have high-resolution elevation data available.

MB-System[6] was used to create the final U.S. Virgin Islands DEMs. The MB-System command 'mbgrid' was used to apply a tight spline tension to the clipped *xyz* data, and interpolate values for cells without data. The resulting binary grid was converted to an Arc ASCII grid using the MB-System tool mbm_grd2arc.

GDAL[7] was used to transform the VIVD09 DEM to MHW using conversion grids generated with *Vdatum* (section 3.2.2).

4.2 Quality Assessment of the DEMs

4.2.1 *Horizontal accuracy*

The horizontal accuracy of topographic and bathymetric features in the U.S. Virgin Islands DEMs are dependent upon the datasets used to determine corresponding DEM cell values (Table 2), the cell size of the DEMs and whether or not the cell value was assigned due to interpolation. The horizontal accuracy is 10 meters where topographic lidar datasets contribute to the DEM cell value. The horizontal accuracy is 0.75 meters at 1 sigma where only bathymetric–topographic lidar-derived data contributes to the DEM cell value. Positional accuracy is limited by: the morphologic change that occurs in this dynamic region.
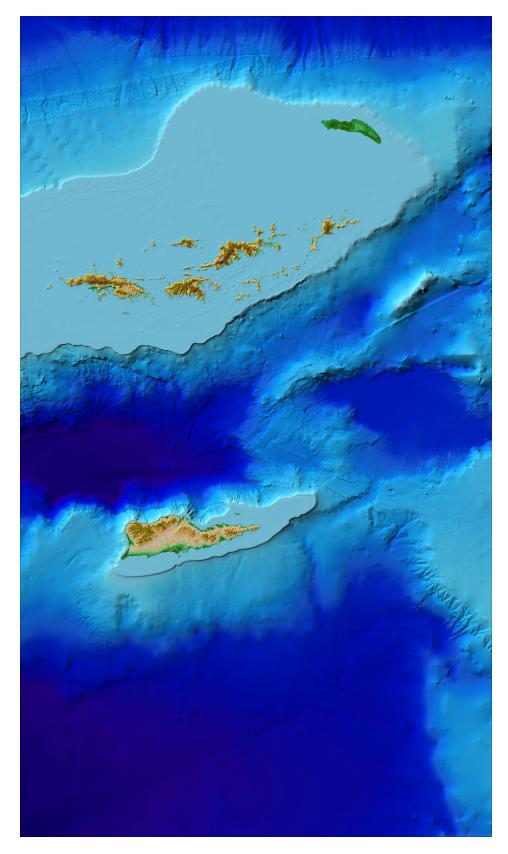
4.2.2 *Vertical accuracy*

Vertical accuracy of the U.S. Virgin Islands DEMs are also highly dependent upon the source datasets contributing to DEM cell values. Bathymetric–topographic and topographic lidar has an estimated RMSE of 13.9 to 20cm. Gridding interpolation was used to determine values between data gaps which degrades the vertical accuracy of elevations in those respective cells.

4.2.3 *Slope maps and Hillshades*

GMT was used to generate slope grids, and GDAL was used to generate hillshades from the U.S. Virgin Islands DEMs to allow for visual inspection and identification of artificial slopes and artifacts along boundaries between datasets (Figures 3 – 5). The DEMs were transformed to UTM Zone 15 North coordinates (horizontal units in meters) in GDAL for derivation of the slope grids; equivalent horizontal and vertical units are required for effective slope analysis. Three-dimensional viewing of the UTM-transformed DEM was accomplished using QTModeler. Analysis of preliminary grids revealed suspect data points, which were corrected before recompiling the DEM.

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[6]MB-System is an open source software package for the processing and display of bathymetry and backscatter imagery data derived from multibeam, interferometry, and sidescan sonars. The source code for MB-System is freely available (for free) by anonymous ftp (point and access through these web pages). A complete description is provided in web pages accessed through the web site. MB-System was originally developed at the Lamont-Doherty Earth Observatory of Columbia University (L-DEO) and is now a collaborative effort between the Monterey Bay Aquarium Research Institute (MBARI) and L-DEO. The National Science Foundation has provided the primary support for MB-System development since 1993. The Packard Foundation has provided significant support through MBARI since 1998. Additional support has derived from SeaBeam Instruments (1994–1997), NOAA (2002–2004), and others. URL: http://www.ldeo.columbia.edu/res/pi/MB-System/ [Extracted from MB-System web site.]

[7]GDAL is a translator library for raster and vector geospatial data formats that is released under an X/MIT style Open Source license by the Open Source Geospatial Foundation. As a library, it presents a single raster abstract data model and vector abstract data model to the calling application for all supported formats. It also comes with a variety of useful commandline utilities for data translation and processing.

Figure 3. *Hillshade image of the U.S. Virgin Islands 1 arc-second DEM.*
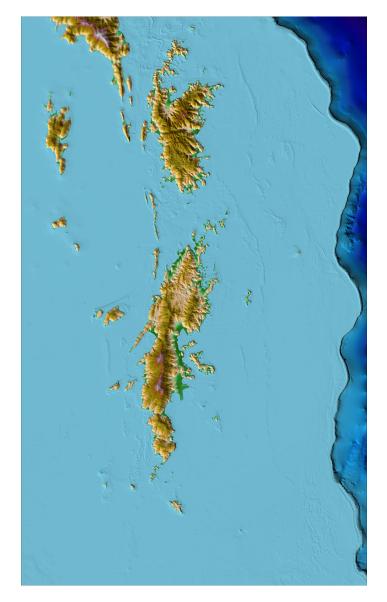
Figure 4. *Hillshade image of the St. Thomas and St. John 1/3 arc-second DEM*
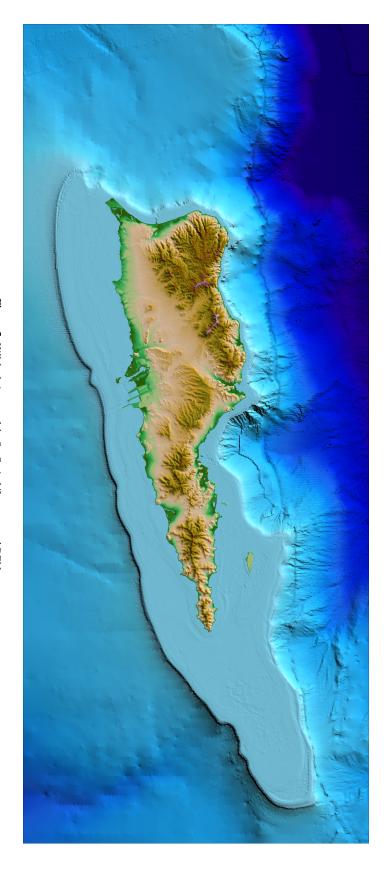
Figure 5. *Hillshade image of the St. Croix 1/3 arc-second DEM*

5.   SUMMARY AND CONCLUSIONS

Three bathymetric–topographic digital elevation models of the U.S. Virgin Islands, with cell spacing of 1/4 arc-second, and a vertical datum of MHW. The DEMs were developed by NGDC for PMEL for use in tsunami generation, propogation and inundation simulations. The best available digital data were obtained by NGDC, shifted to common horizontal and vertical datums, and evaluated and edited before DEM generation. The data were quality checked, processed and gridded using ESRI ArcGIS, GMT, MB-System, QT Modeler, GDAL, Proj4 and Gnuplot software.

Recommendations to improve the U.S. Virgin Islands DEMs, based on NGDCs research and analysis, are listed below:

- Conduct topographic–bathymetric lidar surveys for all near-shore regions not already thus covered.

- Conduct high-resolution hydrographic surveys in hydrographic data gaps and in estuary bays and rivers.

6.   DATA PROCESSING SOFTWARE

ArcGIS 10.1 - developed and liscensed by ESRI, Redlands, California, http://www.esri.com

ESRI World Imagery - ESRI ArcGIS Resource Centers, http://www.esri.com

GMT v. 4.5.9 - Generic Mapping Tools, free software developed and maintained by Paul Wessel and Walter Smith, funded by the National Science Foundation, http://gmt.soest.hawaii.edu

MB-System v. 5.4.213 - free software developed and maintained by David W. Caress and Dale N. Chayes, funded by the National Science Foundation, http://www.ldeo.columbia.edu/res/pi/MB-System

Quick Terrain Modeler v. 6.0.1 - lidar processing software developed by John Hopkins University's Applied Physics Laboratory (APL) and maintained and licensed by Applied Imagery, http://www.appliedimagery.com

GDAL v. 1.10.1 - Geographic Data Abstraction Library is a translator library maintained by Frank Warmerdam, http://gdal.org

Proj4 v. 4.8.0 - free software developed by Gerald Evenden and maintained by Frank Warmerdam, http://trac.osgeo.org/proj/

VDatum v. 3.1 developed and maintained by NOAAs National Geodetic Survey (NGS), Office of Coast Survey (OCS), and Center for Operational Oceanographic Products and Services (CO-OPS), http://vdatum.noaa.gov/